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14. ABSTRACT As the use of advanced composite materials continues to expand into new technology areas, a troublesome issue arises involving the inability of mainstream designers to accurately predict the initiation and growth of the material damage under multiaxial stress states. This shortcoming was clearly illustrated in impressive fashion under the recent "World Wide Failure Exercise". The inability to predict the load response of composite materials in the region of their ultimate load has been primarily attributed to both incomplete development of a general compoisite failure theory and insufficient multiaxial experimental data for verification. To this end, an ongoing analytical and experimental effort was pursued by the authors. A thickness-tapered cruciform specimen was developed and shown to be capable of producing acceptable multiaxial results for specific composite laminate architecture. The electromechanical test facility at the Air Force Research Laboratory, Space Vehicles Directorate, is capable of generating any combination of tensile or compressive stresses in σ_1: σ_2:σ stress space. To date, biaxial tests and numerical predictions were performed on two laminate stacking sequences, cross-ply and quasi-isotropic, and two material systems, carbon/epoxy and E-glass/vinyl ester. The results between analytical predictions generated using Multicontinuum Theory (MCT) will be correlated with mutliaxial experimental results providing further insight to the capabilities of the current experimental approach.

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RECENT BIAXIAL TEST RESULTS OF LAMINATED COMPOSITES AND ANALYTICAL MCT PREDICTIONS

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ABSTRACT

As the use of advanced composite materials continues to expand into new technology areas, a troublesome issue arises involving the inability of mainstream designers to accurately predict the initiation and growth of the material damage under multiaxial stress states. This shortcoming has been clearly illustrated in impressive fashion under the recent "World Wide Failure Exercise". The inability of predict the load response of composite materials in the region of their ultimate load has been primarily attributed to both incomplete development of a general composite failure theory and insufficient multiaxial experimental data for verification. To this end, an ongoing analytical and experimental effort has been pursued by the authors. More specifically, a thickness-tapered cruciform specimen has been developed and shown to be capable of producing acceptable multiaxial results for specific composite laminate architectures. All biaxial tests were performed utilizing a triaxial testing facility located at the Air Force Research Laboratory, Space Vehicles Directorate. This electromechanical test facility was developed specifically to evaluate the biaxial (in-plane) and triaxial (three-dimensional) response of composite materials. This experimental test facility is capable of generating any combination of tensile or compressive stresses in $\sigma_1{:}\sigma_2{:}\sigma_3$ stress space. To date, biaxial tests and numerical predictions have been performed on two laminate stacking sequences, cross-ply and quasi-isotropic, and two material systems, carbon/epoxy and E-glass/vinyl ester. A discussion of the advantages, challenges, and accuracy inherent in the thickness-tapered cruciform specimen's ability to accurately evaluate the biaxial strength of fiber-reinforced composites will be presented. The results between analytical predictions generated using Multicontinuum Theory (MCT) will be correlated with multiaxial experimental results providing further insight to the capabilities of the current experimental approach.

KEY WORDS: Testing/Evaluation, Composite Materials, Finite Element Analysis

1. INTRODUCTION

As the evolution of modern fiber reinforced composite materials continues to make strides in terms of material performance, quality, quantity, and price there are areas that have struggled to make substantial improvements. Perhaps most notable are the failure theories that have evolved from isotropic materials have proven to be far less effective for anisotropic composite materials [1-5]. As a result of the uncertainty associated with inaccurate failure theory predictions, design engineers are forced to use overly conservative designs that ultimately hinder the continued application of composites to many structures. Of the progress that has been made towards the development of accurate failure theories, a recent trend towards micro-level failure theories is beginning to emerge as a promising approach [1]. This trend most likely being a result of increased computational power coupled with growing frustration in the composites community with its collective inability to consistently design efficient composite components.

The desire to improve predictive capabilities has generated sufficient interest in the past decade to warrant accelerated evaluation and development of numerous new approaches. While the independent development of these theories has resulted in a significant amount of literature, the community-wide assessment of the current state of the practice by Hinton, Kaddour, and Soden [3], is particularly notable as it serves as a recent benchmark for the industry. Although not all-inclusive, this round-robin study was quite successful in illuminating the current capability of the composites community to predict initial and final failure events of many common composite material systems and laminate configurations. Even with laminate configurations and material systems that are generally accepted in the composites community as being well-understood and widely used no two prediction methods generated identical biaxial (two-dimensional) failure envelopes. Ultimate strength predictions were reported to differ as much as 900% for some cases.

While the direct comparison of the failure prediction methods was the primary objective of the decade-long study by Hinton, Kaddour, and Soden, the present authors believe that an equally important result of that study was that it demonstrated to the composites community the strong need for development of reliable experimental data for multiaxial loading. The foundation of a round-robin type study is accurate experimental data for which to compare analytical predictions. This study demonstrated that there is a very limited amount of multiaxial experimental data in the open literature [1,2,5-7]. In fact, Hinton et al indicated that the primary limitation to the study was the lack of experimental data and acknowledged that a portion of the data used was questionable [8]. Additionally, they acknowledged that for certain laminate configurations and material systems, no data existed in some quadrants of biaxial stress space.

This paper presents recent efforts by the authors to develop experimental biaxial data and an associated failure prediction methodology. More specifically, the development of a thickness-tapered cruciform specimen was used to generate the experimental data while the failure predictions were based on Multicontinuum Theory (MCT) [9-16]. The authors, while acutely aware of the difficulties associated with the development of accurate failure predictions and experimental data, do feel there are some advantages to simultaneously developing both failure prediction methodology and experimental techniques [17,18]. While a thorough presentation of either the MCT analytical foundation or the biaxial experimental techniques is beyond the scope of the present paper and can be found elsewhere [17,18], an overview of the biaxial testing, the MCT failure prediction methodology and a comparison of the results obtained by both will be provided.

2. AFRL TRIAXIAL TESTING FACILITY BACKGROUND

All experimental data presented herein was generated using the Triaxial Test Facility shown in Figure 1. This electromechanical test facility was developed specifically to evaluate the biaxial (in-plane) and triaxial (three-dimensional) mechanical response of composite materials. To date, this facility has been used to evaluate AS4/3501-6 carbon/epoxy, IM6/3501-6 carbon/epoxy, and E-glass/8084 vinyl ester material systems in either cross-ply or quasi-isotropic laminate configurations [9-11,18].

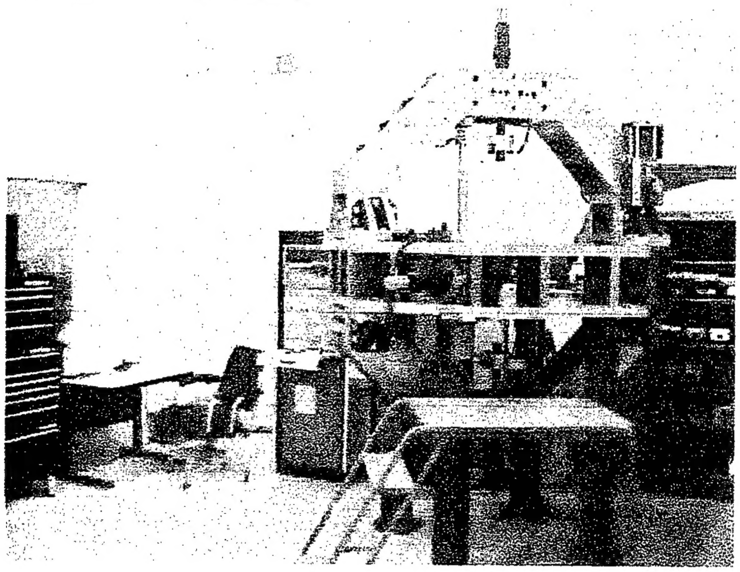

Figure 1. Photograph of the Triaxial Test Facility.

The test facility shown in Figure 1, while primarily used as a reaction frame to apply the loads, makes use of a test fixture for precise test specimen alignment relative to applied loads as shown in Figure 2. The Triaxial Test Facility is capable of generating any combination of tensile or compressive $\sigma_{11} - \sigma_{22} - \sigma_{33}$ stresses [16,18]. This facility is located at the Spacecraft Component Technology Branch, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, NM. It represents a 2^{nd} generation multiaxial test frame. The facility has a capacity of ± 133 kN on each of 6 computer-controlled actuators and is limited to quasi-static test rates only. The relative position of five of the six force actuators (one located below the test fixture) can be seen in Figure 2. All biaxial tests performed in the present study were performed using the four in-plane actuators shown in the horizontal plane of Figure 2.

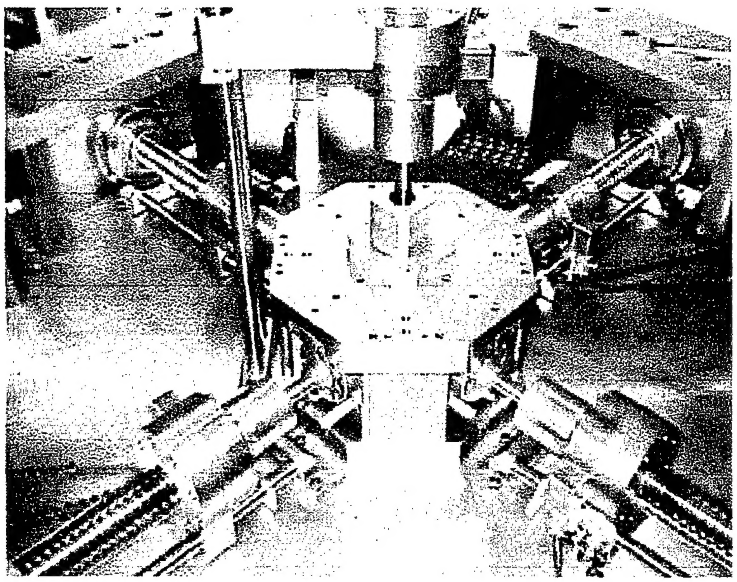

Figure 2. Photograph of the Triaxial Test Fixture.

3. BIAXIAL TESTING BACKGROUND

Throughout the development of the Triaxial Test Facility, the primary concern was to develop an experimental technique that would be capable of generating accurate experimental data. While any researcher, the present authors included, are never absolutely certain that this is being achieved in any experiment, there are numerous steps that can be taken to facilitate precision and accuracy in attempting to generate experimental data. For the present study, the steps taken included precisely fabricating (CNC machining) test specimens to increase the likelihood of statistically consistent experimental data, careful evaluation of each tested specimen to insure that failure occurred in the gage section, correlating with existing experimental results, and correlating with analytical predictions.

Unfortunately, the ability to directly compare experimental biaxial data for exactly the same material systems and laminate configurations for composite materials was not possible due to the incomplete nature of existing data sets in the open literature. That is, outside of the experimental data generated by the present authors, it is exceedingly difficult to find a single data set for any composite material or laminate configuration that provides experimental validation of the biaxial strength for all combinations of biaxial in-plane loading conditions that was performed by a single researcher using a single test configuration. Rather, most complete data sets are a compilation of data obtained by a variety of test methods, that may or may not be consistent, performed by multiple researchers that ultimately generates significant concern as to the validity of the data set as a whole.

To support the goal of consistent data, a single test specimen configuration was designed for all plane (bi-axial) loading conditions, Figure 3. The transitions regions, from loading arm to gage section, are of critical importance because of the obvious potential for stress amplification due to the geometric discontinuity. A significant amount of analysis and trial-and-error experimentation was conducted to minimize the potential corrupting effects of the transition

region of the cruciform specimen. CNC machining tapered the thickness from the griping to the gage sections by approximately 50% using top and bottom fillets. Further, compound radii transitioned the single-axial stress state of the orthogonally loaded arms into the multi-axial stress state of the gage section.

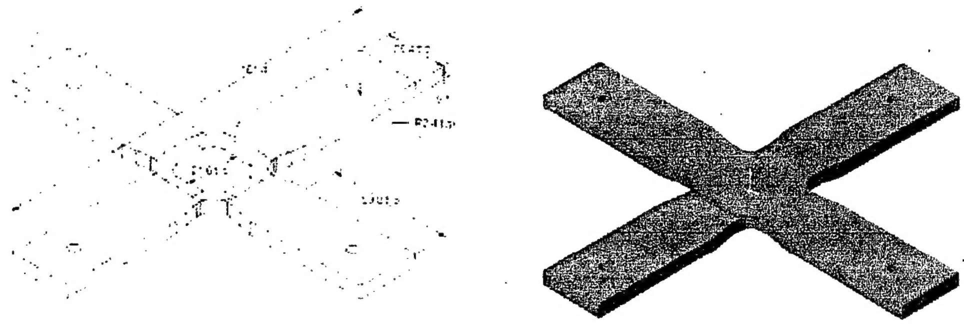

Figure 3. Thickness-Tapered Cruciform Specimen Schematic (dimensions in mm).

To gage the success of efforts to minimize the influence of the cruciform's geometric discontinuity on the determination of a materials ultimate biaxial strength, the first thickness-tapered tests were performed on 6061-T6 aluminum. The biaxial failure envelope generated for this material is shown in Figure 4. As shown, the experimental data were in close agreement with the widely-accepted Tresca and von Mises failure predictions for a homogenous, isotropic material. This motivated the authors to extend the procedure to tests of nonhomogenous, orthotropic composite materials.

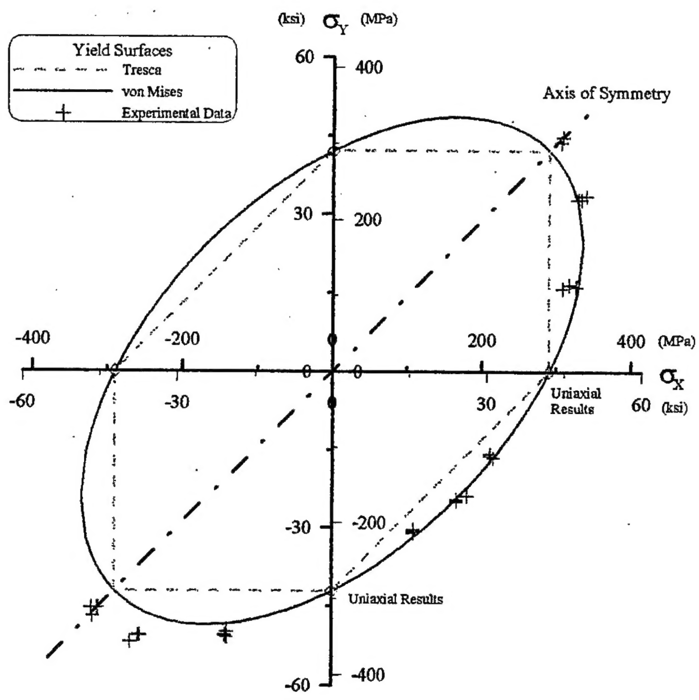

Figure 4. Biaxial Failure Envelope for 6061-T6 Aluminum.

4. COMPOSITE BIAXIAL TESTING DEVELOPMENTS

While there have been numerous variations of the thickness-tapered cruciform specimen shown in Figure 3 that are not detailed in this paper, there are many general conclusions that are common to all tests performed using the cruciform specimen configuration that are described in this section. The interested reader is referred to the more detailed citations found in the references.

In making the transition from testing a relatively ductile, homogenous, isotropic aluminum material to a brittle, nonhomogeneous, anisotropic, laminated composite material, additionally concerns were raised. To be considered a successful biaxial test, ultimate specimen failure must occur in the gage section of the test specimen. Biaxial strengthening effects exhibited by many materials, i.e., ultimate material strengths higher in multi-axial stress states than uniaxial, can make this a difficult objective to obtain. This phenomenon can be seen in Figure 3 and is predicted by most higher-order, stress-interactive failure theories [3]. In general, a biaxially strengthened failure envelope shape is an ellipse in 2-D with the major axis along a 45° line through the first and third quadrants in of rectangular $\sigma_{ii} - \sigma_{jj}$ coordinates. For composite laminates, the biaxial strengthening can be even more pronounced than for isotropic materials [7]. Using biaxial cruciform specimens, it is reasonable to expect unacceptable failures to occur in one of the loading arms which are loaded uniaxially rather than in the biaxially loaded gage section of a general laminate. Cross-ply laminates, as a result of their low in-plane Poisson's response, appear to have minimal biaxial strengthening and have been successfully tested in previous studies [10,11,18]. This is one of the reasons the thickness-tapered cruciform was deemed a viable test specimen configuration. Previous experience of the authors on other research projects led us to believe that a quasi-isotropic laminate, which exhibit a larger in-plane Poisson's response than the cross-ply, could be successfully tested with the appropriate specimen geometry. Testing of quasi-isotropic laminates will be more fully discussed in following sections.

One unique aspect of using thickness-tapered cruciform specimens to determine the biaxial strength of laminated composites is that specific measures must be taken to generate accurate results. Because cruciform-shaped specimens have two intersecting loading directions, there exists the possibility of load sharing between adjacent loading arms. That is, it is possible that all of the applied load in one direction may not be directed into the gage section, leading to inaccurate stress level predictions in the biaxially loaded gage section. Fortunately, it is possible, but not trivial, to quantify the levels of load sharing for each material system and specimen geometry, as was done in the present study. Referred to as the *bypass correction factor*, this value, which is laminate and material depended, provides a measure of the amount of applied force that bypasses the thickness-tapered gage section. The bypass correction factor is then used to adjust the as-measured ultimate biaxial failure strength after each experimental test has been performed.

Because of the importance of utilizing the bypass correction factor to accurately assess the stress state in a thickness-tapered cruciform specimen, considerable effort has been expended establishing its value for each laminate and material tested. Finite element analysis (FEA) has been used to generate bypass factors to compare against experimentally determined values. Figure 5 illustrates the load reaction force distribution from the center of the gage section ($0 < y < 0.6$), through the thickness taper fillet ($0.6 < y < 1$), into the arm transverse to the load being examined ($1 < y$), generated using FEA. These results are for a balanced cross-ply,

carbon/epoxy material system using both composite shell elements and continuum (3-D solid) elements. The bypass correction factor for this specific configuration was found to be 0.875 and 0.883 for the composite shell elements and continuum elements, respectively. These values represent the fact that approximately 88% of the force applied to the loading arms of the thickness-tapered cruciform specimen is reacted by the biaxially-loaded gage section, i.e., approximately 12% of the load "bypasses" the gage section. The analytical value is within 5% of the experimentally determined bypass correction factor for this laminate configuration. Similar results were observed for other laminate architectures.

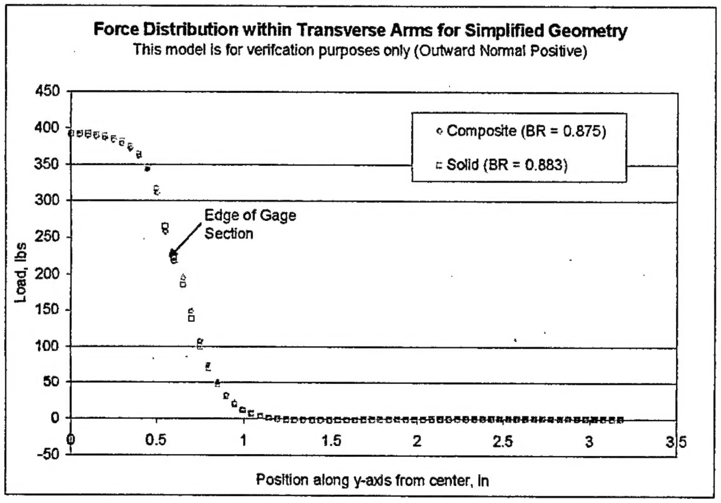

Figure 5. FEA Bypass Ratio Validation for IM7/977-2 Carbon/Epoxy Cross-Ply Laminates.

Another reasonable concern when dealing with the bypass correction factor and thickness-cruciform test specimens is whether the bypass correction factor remains constant over the duration of a test. Because specimen geometry changes slightly during its progression to ultimate failure, the possibility that the bypass correction factor changes as a function of applied load was investigated. As shown in Figure 6, the experimentally-determined bypass correction factor, as a function of applied load, remains essentially constant during the duration of a static biaxial test. Based on the encouraging results presented in Figures 4 – 6, the thickness-tapered cruciform specimen appears to be capable of generating acceptable experimental biaxial data for composite laminates. Details of the experimental results generated using this technique will be presented in following sections.

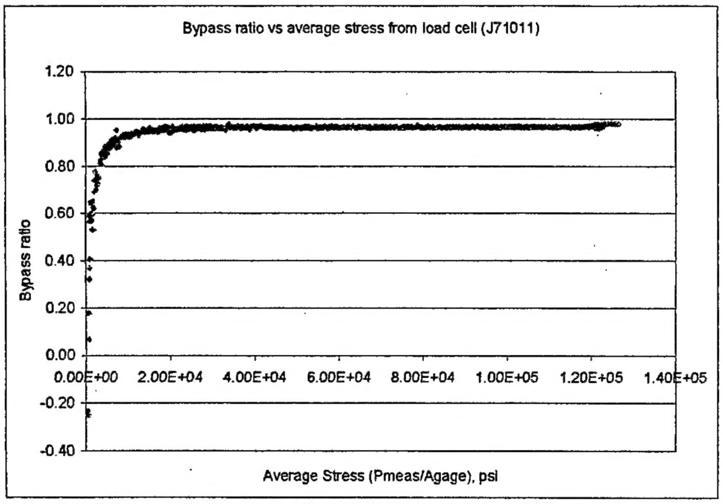

Figure 6. FEA Bypass Ratio Determination for IM7/977-2 Carbon/Epoxy Cross-Ply Laminates as a Function of Applied Load.

5. MULTICONTINUUM THEORY (MCT) BASICS

The Multicontinuum Theory (MCT) analysis used in the present study is, simply stated, a concept that is capable of describing multiple phases, i.e., coexisting continua, within a single material point. Noting that damage in a composite material typically begins at the constituent level and may be in fact limited to only one constituent in some situations, a MCT analysis is ideally suited to the analysis of composite materials. MCT [12-15] is a highly efficient combination of micro- and macro-mechanics that utilizes the classic strain decomposition approach of Hill [19] to extract the constituent stresses from those of the composite they form. The constituent stresses are used as inputs to a quadratic stress-interactive constituent based failure criteria [12]. The result is a progressive, non-linear analysis technique for the simulation of failure in structures made from composite materials. The interested reader is referred to the cited literature for more details regarding the specific formulation and implementation of MCT.

Traditionally, most analytical approaches rely on homogenizing the composite constituent's material properties into an idealized homogenous lamina and then homogenizing the individual lamina material properties into an idealized homogenous laminate to attain uniform strength and stiffness. While this 'smearing' approach is fairly successful in developing laminate stiffness properties, it masks large internal stress associated with constituent interactions due to their microstructure. MCT assumes a particular fiber packing in an idealized unidirectional lamina, Figure 7a. A representative volume element (RVE), Figure 7b, is identified and used to determine the parameters necessary to decompose the constituent's strain fields from those of the lamina. The decomposition is done separately from any analysis of a composite structure decoupling the micro- and macro-analyses which boost the computational efficiency significantly.

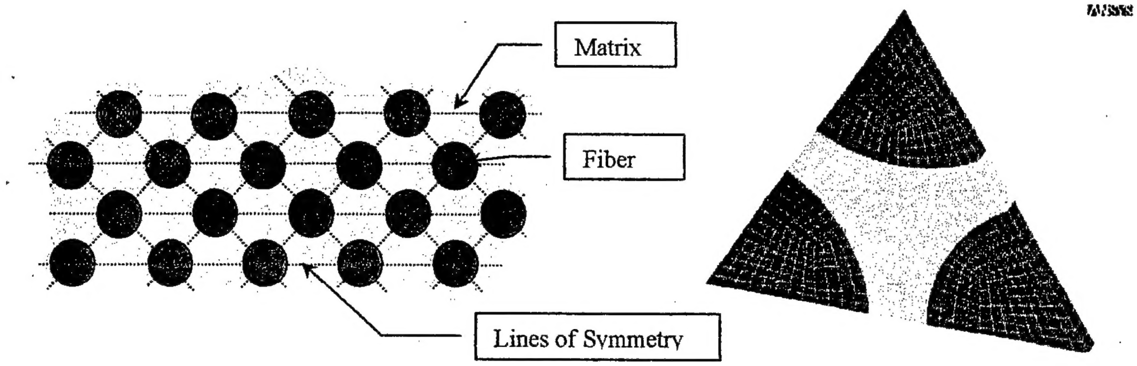

Figure 7. Idealized Lamina Microstructure for the Two Constituent Model and FEA Representative Volume Element (RVE).

The MCT approach can be applied to differing micro-structures that reflect the composite's constituents. In the present study, the two constituent microstructure (fiber and matrix), Figure 7, was used to generate biaxial failure envelopes laminates made from unidirectional carbon/epoxy lamina. Only three composite damage states are assumed: undamaged, failed matrix, and failed fiber. The three constituent microstructure (warp roving, fill roving, and matrix), Figure 8, was used to generate biaxial failure envelopes for laminates made from woven fabric lamina. Five composite damage states are assumed: transverse failure of the warp roving (matrix failure within the roving), longitudinal failure of the warp roving (fiber failure within the roving), transverse failure of the fill roving, longitudinal failure of the fill roving, and combined transverse failure of both the warp and fill roving.

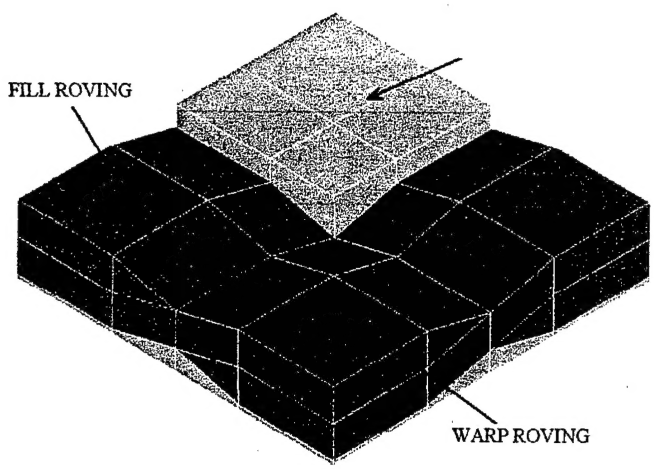

Figure 8. Micromechanics RVE Model for a Plain Weave Fabric.

6. EXPERIMENTAL DATA AND MCT PREDICTIONS

A total of five laminate configurations have been tested to date using the Triaxial Test Facility and the procedures previously described. Those laminates include an AS4/3501-6 carbon/epoxy $[0/90]_{NS}$, an IM6/3501-6 carbon/epoxy $[0/90]_{NS}$, an IM7/977-2 carbon/epoxy $[0/90]_{NS}$, a woven E-glass/vinyl ester $[0/90]_{NS}$, and a woven E-glass/vinyl ester $[0/90/\pm 45]_{NS}$.

Below are experimentally determined biaxial failure envelopes for each material system will be presented along with a MCT generated counterpart when available. Each graph is followed by a brief discussion. The interested reader is referred to the cited references for additional details.

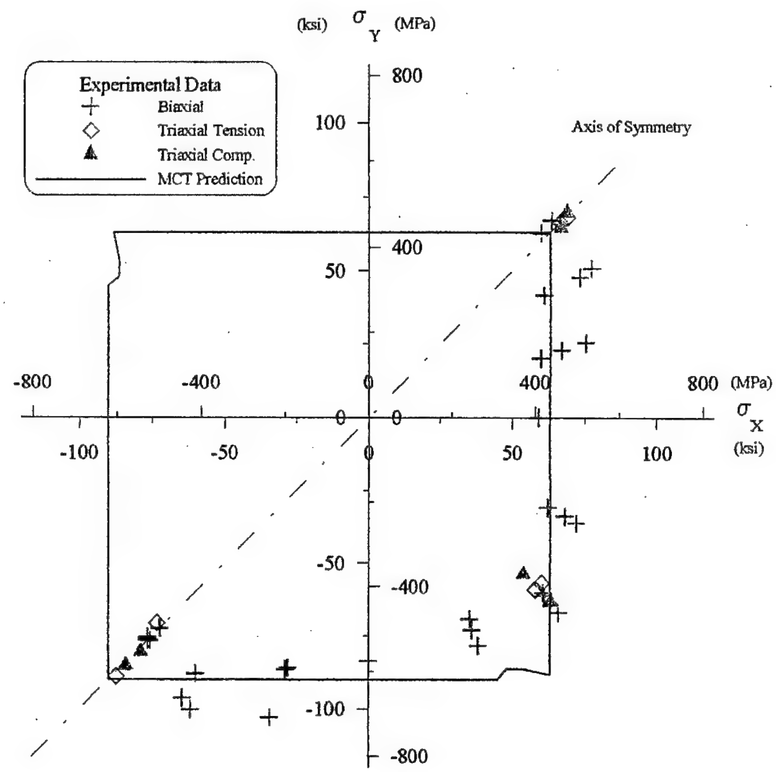

Figure 9. Biaxial Failure Envelope for an AS4/3501-6 Carbon/Epoxy $[0/90]_{NS}$ Laminate.

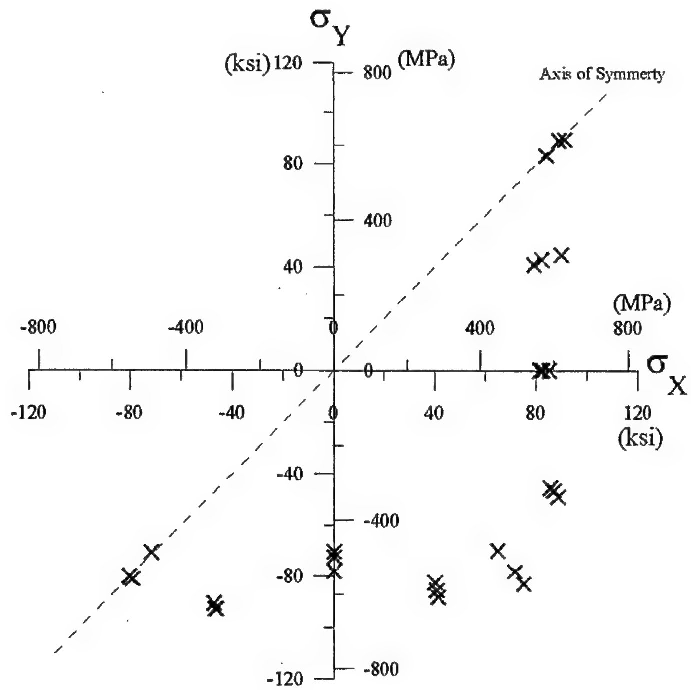

Figure 10. Biaxial Failure Envelope for an IM6/3501-6 Carbon/Epoxy $[0/90]_{NS}$ Laminate.

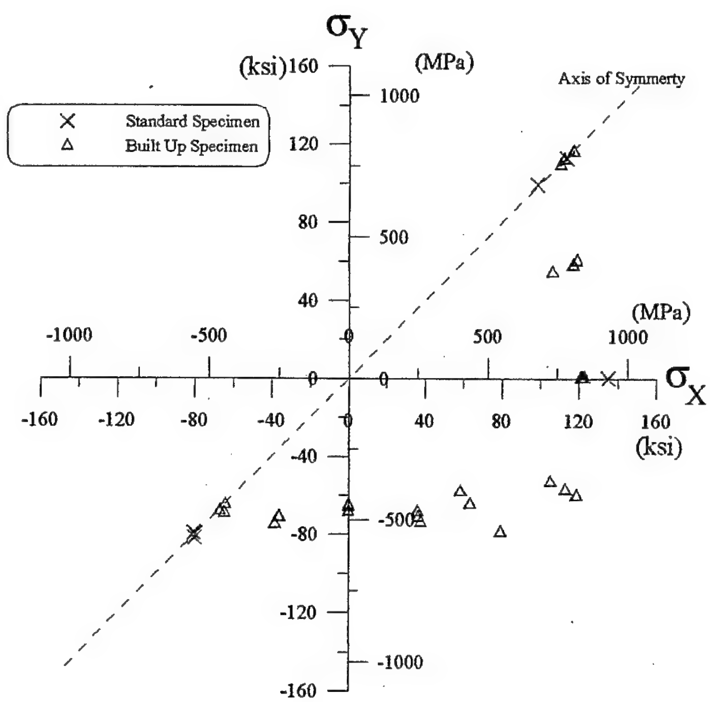

Figure 11. Biaxial Failure Envelope for an IM7/977-2 Carbon/Epoxy $[0/90]_{NS}$ Laminate.

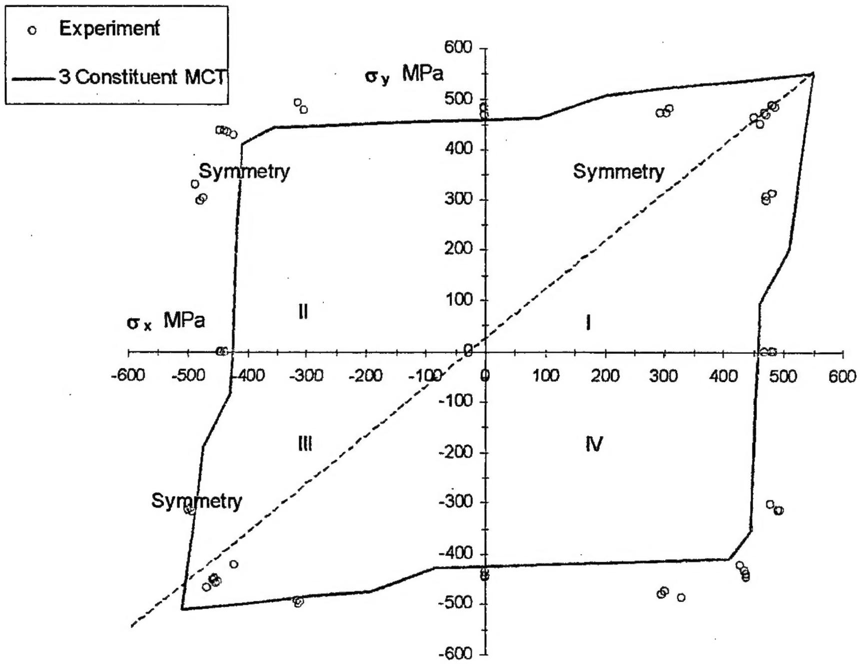

Figure 12. Biaxial Failure Envelope for an E-Glass/Vinyl Ester $[0/90]_{NS}$ Laminate.

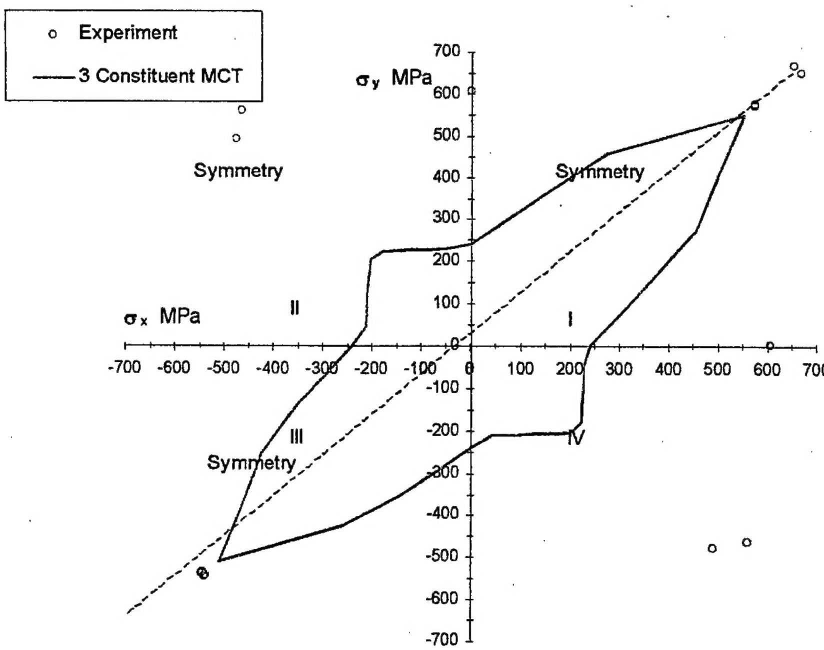

Figure 13. Biaxial Failure Envelope for an E-Glass/Vinyl Ester $[0/90/\pm45]_{NS}$ Laminate.

The data presented in Figures 9-13 represents a consolidation of nearly a decade of research and although the test methods have evolved, there are many general statements that may be made regarding the data presented. Perhaps the most significant aspect of the data presented in Figures 9-12 is that they represent a complete data set in $\sigma_1 - \sigma_2$ stress space. Irregardless of the specific data presented in the previous biaxial failure envelopes, it is difficult, if not impossible, to find data sets comparable to these for a single materials system performed by a single researcher. Additionally, the biaxial compression (quadrant 3 in Figures 9-13) data represents a significant percentage of the total biaxial compression that has been presented in the open literature. Difficulties associate with bucking of biaxial compression specimens have frustrated previous investigators to the point where extremely limited data has been generated to date [7]. The fact that the present test method has demonstrated the ability to generate experimental data in all quadrants of stress space (noting the obvious line of symmetry in each data set) by utilizing a test specimen that can relatively easily be fabricated from a flat laminate, lends considerable credibility to the approach detailed in the present paper.

The close correlation of MCT's analytically generated failure envelopes with the experimentally generated ones help validate the experimental approach. It is noted that for each data set presented in Figures 9-12 the failure envelope could be reasonably approximated by a max stress/strain prediction. While this result may seem simplistic, we did not anticipate it when we began the program and it is gratifying to see MCT accurately predict such an outcome. The rectangular failure envelope is not totally unexpected as the laminates tested for those data sets were all balanced cross-ply configurations. Additionally, the cross-ply laminates tested for the present study did not exhibit a significant amount of biaxial strengthening effects. It is precisely for this reason that this laminate configuration was a good selection for initial development of the biaxial test methods detailed in this paper. All of the experimental data presented in Figures 9-13 were obtained from tests in which specimen failure initiated in the gage section of the test specimen.

It is also worth noting that the data presented in Figure 13 for the quasi-isotropic laminate did not demonstrate the level of biaxial strengthening effects anticipated, as evident by the MCT prediction shown in Figure 13. The specific reason that this effect was not seen is not definitively known, but will be the subject of future research efforts by the authors.

7. CONCLUSIONS

The favorable and complementary failure surfaces obtained in the present study are verification for the experimental techniques used to determine the biaxial strength of fiber reinforced composite laminates. Concerns associated with stress concentrations near the gage section of cruciform specimens have been diminished by the numerical predictions and visual appearance of failure areas obtained in the present study. At the very least, the biaxial failure envelopes generated herein represents a reasonable approximation of laminate strength throughout the entire two-dimensional $\sigma_{ii} - \sigma_{jj}$ stress space for this material. Continued development of the techniques used in the present study ensures that much-needed experimental biaxial data on this and other materials will be generated.

The authors recommend that future research efforts be focused on generating a complete failure envelope for the quasi-isotropic fabric reinforced laminate. This laminate offers the opportunity to build on the results of the cross-ply laminate in a systematic way. The addition of the ±45° lamina creates an in-plane triaxial lamina stress state, two normal and one shear stress,

requiring a rigorous test case for evaluating failure analysis methodologies. Additionally, determination of the biaxial strengthening effect of laminated composites can be easily evaluated using this laminate configuration.

8. ACKNOWLEDGEMENTS

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